Exploring the Ocean through Sound

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Abstract

Sound is an important sensory modality in the lives of many marine organisms, as sound travels faster and farther than any other sensory signal. Consequently, marine animals ranging from the smallest larvae to the largest whales have evolved mechanisms for both producing and receiving acoustic signals. Innovation in underwater recording technology now permits the remote monitoring of vocalizing animals and the environment without the need to rely on human observers, the physical presence of an ocean observation vessel, or adequate visibility and sampling conditions. Passive acoustic monitoring is an efficient, non-invasive, and relatively low-cost alternative to hands-on exploration that is providing a wealth of information on regional sound sources (biologic, anthropogenic, geophysical), animal behavior, ecosystem dynamics, biodiversity, and impacts of human activity

Key Words

Soundscape, ambient sound, soundscape ecology, orientation, biodiversity

The average depth of the ocean is 4000 m. Light only penetrates the first 100 m, yet life abounds below this photic zone. Marine life establish homes, find food, socialize, mate, and raise young while avoiding predators, all without light. Ocean water is approximately 1000 times denser than air resulting in ocean sound speeds that are approximately five times higher than in air with much lower attenuation, so that sound travels further and faster in water than air. Marine life has evolved to use sound as a primary sensory modality for interacting with their environment. Fascinating examples include crustacean larvae that listen for the sound of the right type of reef to settle on, snapping shrimp that generate bubbles whose sound stuns prey, fish that drum their swimbladders during mating seasons, blind river dolphins that navigate and socialize using clicking sounds, and the long moans of blue whales that can travel 1000’s of km.

Similar to air, water’s density depends on temperature, depth, and the chemical composition of the salts in the water. Like oil on water, warm and less salty water will float on colder, salty water. Ocean currents, solar heating, river inputs, and upwelling create layers of water with different densities, which then have different sound speeds. As sound travels through these layers it reflects and refracts in complex ways (Figure 1). Physics dictate that sound propagates in the direction of water regions with the lowest sound speed, resulting in channels (surface or deep water) that retain the propagating sound (Figure 1). Consequently, sounds from low-frequency sources like ships, seismic airguns, and blue whales transmit 1000’s of km in the deep ocean and can be combined to contribute to local soundscapes, making sound one of the most accessible tools for exploring the ocean.

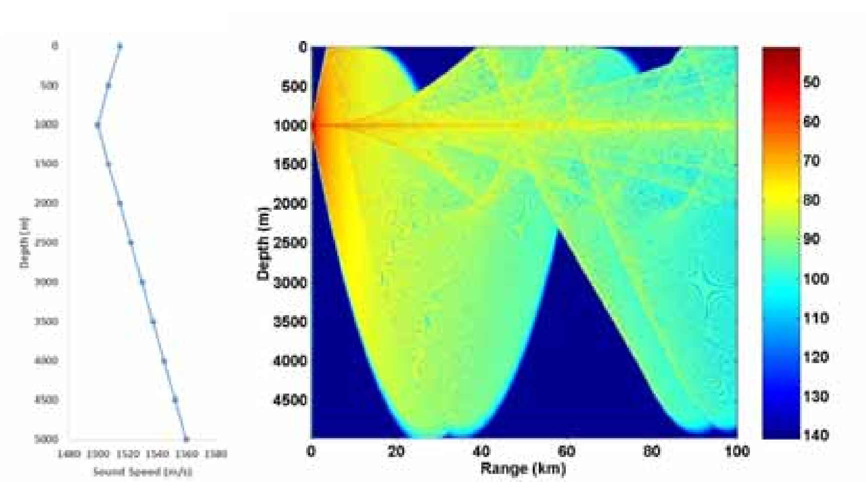
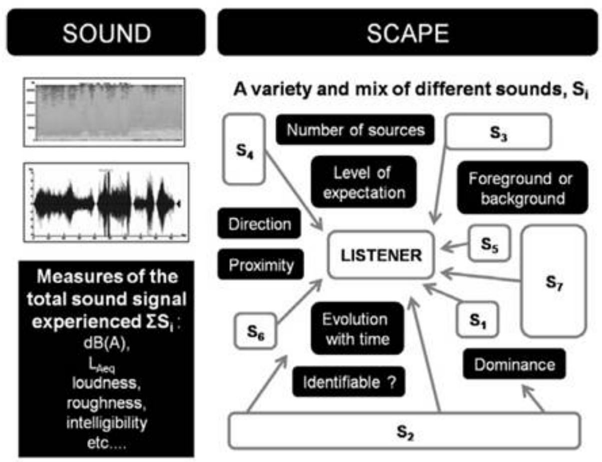


Figure 1. Propagation of a 200 Hz signal in the deep sound channel at mid-latitude with a source depth of 1000 m. Color bar = Transmission Loss (dB)

Tomograph

y sources measure the time it takes sound to travel long distances to explore changes that are linked to global climate change. Seismic airgun arrays look at the earth's structure far below the seabed. Passive listening provides information on the presence and activities of marine life and humans, as well as the background sounds made by wind and waves. The remainder of this paper describes how advances in low-cost passive acoustic technology are providing long term data sets that have inspired new analysis techniques to better understand the complex interactions between marine life, the environment, and mankind.

Soundscapes



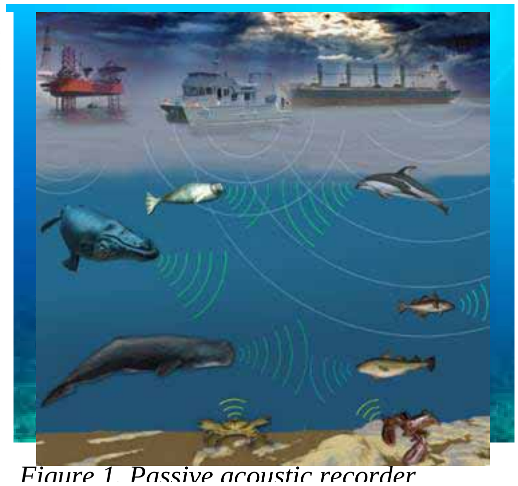


Figure 1. Passive acoustic recorder

Figure 2. Left **-** *A soundscape conveys how all of the sound sources overlap and are perceived by the listener [Figure from (Jennings and Cain, 2013)[1]]. Right - Graphic representation of the multiple ocean sources contributing to an ocean soundscape [Figure from NOAA's Ocean Noise Strategy (http://www.nefsc.noaa.gov/psb/acoustics/psbAcousticsOceanNoiseStrategy.html)].*

Passive acoustic monitoring is performed using autonomous recorders that are left on the seabed or in the water column for up to one year at a time (Figure 2). The recordings allow us to observe marine habitats without the confounding effects of human presence or sampling biases. A great deal of information related to ocean dynamics and ocean use can be gained simply by listening to the ambient sound field, or soundscape. The soundscape, or auditory landscape, is a combination of the traditionally measured physical sound signal and the dynamically changing acoustic environment. It is composed of multiple sound sources, the perception of which depends upon the relative contribution of each source, its direction, the propagation of the signals, behavioural context of the listener, and history of the listener with similar sounds (**Error! Reference source not found.**). Marine animals and humans both heavily rely on acoustic cues contributing to soundscapes to gain information about their surroundings. A large number of aquatic species use sound cues contained in local soundscapes to navigate, forage, select habitat, detect predators, and communicate information related to critical life functions (e.g. migration, breeding, etc.).

Passive acoustic monitoring data can be selectively decomposed and visualized to gain a greater understanding of the sources and environmental dynamics contributing to and shaping the temporal, spatial, and spectral patterns of the acoustic environment (Figure 4). To date, there is no standardized format for visually representing a soundscape or the difference between soundscapes. However, soundscape analyses have provided a means for better understanding the influences of environmental parameters on local acoustic processes [2-4], assessing habitat quality and health [4-5], measuring biodiversity [5-6] and for better understanding the impacts and risks of human contributions to the soundscape have on marine life.

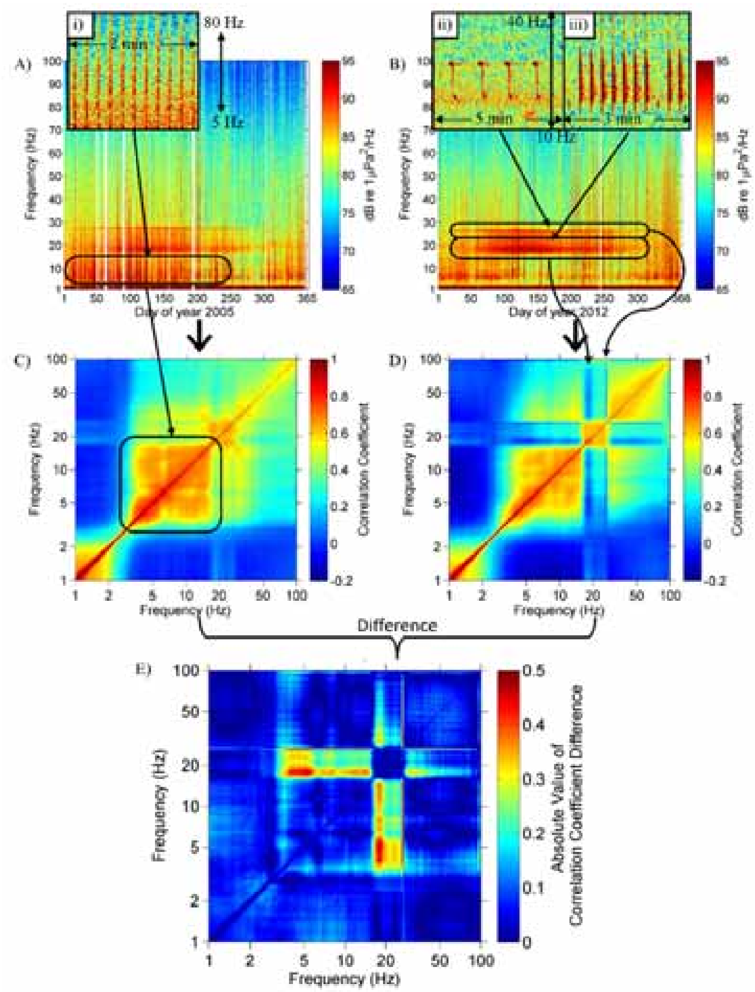


Figure 4. Panels A and B are simple, unfiltered spectrograms (time-frequency representations) of a year of data recorded from Ascension Island in the South Atlantic Ocean in 2005 (A) and 2012 (B). Inset (i) shows seismic airgun signals as the dominant source in 2005, whereas whale vocalizations (Inset (ii) – Antarctic blue whales, Inset (iii) – fin whales) dominated the soundscape in 2012. Panels C and D were created by cross-correlating the spectral content of A and B, respectively, to highlight spectral differences between soundscapes in the 2 years. Panel E was created by subtracting the information from Panels C and D to create a Correlation Difference Matrix. The Correlation Difference Matrix is used to easily identify the frequencies that changed the most during the two time periods and provides a quantitative measure of soundscape change. Reproduced from Miksis-Olds & Nichols (2016) Figure 4 [7].

Underwater soundscapes are dynamic in that they vary in space and time within and between habitats. They are highly influenced by local and region conditions, but unlike most terrestrial soundscapes, distant sources can also significantly contribute to local and regional soundscapes because sound propagates such great distances underwater (**Error! Reference source not found.**). The underwater soundscape is composed of contributions from human activity (e.g. shipping, fishing, seismic airgun surveys; Figure 4; Figure5 –Red Box), natural abiotic or geophysical processes (i.e. wind, rain, ice), non-acoustic biotic factors (e.g. animal movement), and acoustic contributions from vocalizing, biological sources (e.g. marine mammals, fish, and invertebrates; Figure 4; Figure5 – Green Boxes). One way arrows in Figure 5 show that the soundscape is directly influenced in a single direction by

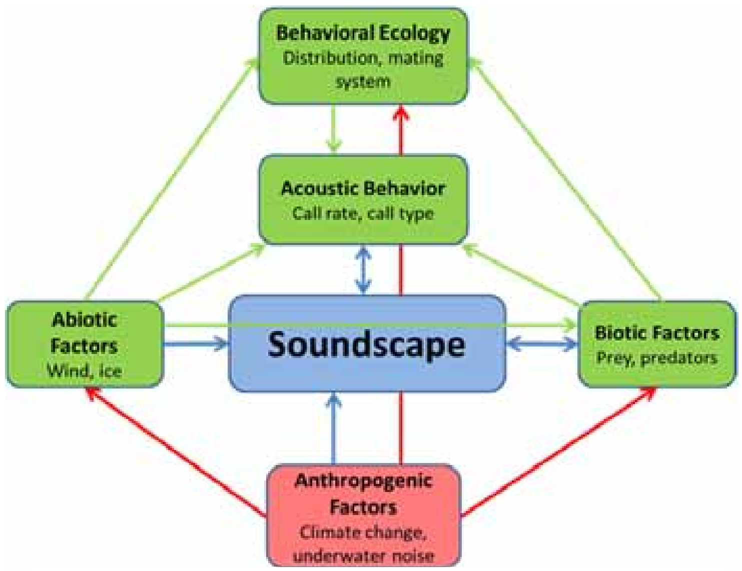


Figure 5. Soundscape presented within the context of acoustic ecology (adapted from Figure 1 of van Opzeeland & Miksis-Olds (2012) [8].

anthropogenic and abiotic factors, whereas double-headed arrows indicate the that soundscape is not only influenced by, but also influences the biological soundscape component [8]. Consequently, the underwater soundscape is not merely a physical parameter of the environment to be measured and quantified. The soundscape depends on the listener and has a feedback loop where changes in soundscape have the potential to impact acoustic behavior and biotic factors which influences the behavioral ecology of the ecosystem and ultimately further alters the soundscape (Figure 5).

Successes using passive soundscapes to explore the oceans

Over the past decade the costs of collecting and analyzing passive acoustic monitoring data have been steadily decreasing, leading to an increasing number of studies that explore how animals use information from their environmental soundscape for communication, orientation, and navigation [9-12]. The concept of using ambient or reflected sounds (as opposed to specific communication signals) to direct movement or identify appropriate habitats has recently been identified as a new field of study referred to as *soundscape orientation*, and the concept is also included within the broader field of *soundscape ecology* in the scientific literature [9-10]. It has been speculated that large baleen whales use ambient acoustic cues or acoustic landmarks to guide their migration [13-14]. Similarly, it has been proposed that ice seals could utilize aspects of the soundscape to gauge their safe distance to the ice edge by orienting in the direction of higher sound levels indicative of open water [15]. Frequencies of 10-40 kHz were identified as strong predictors of ice seal vocal presence in the Bering Sea during the breeding season, yet seals don't vocalize in this frequency range [15-16]. There was a 20-30 dB difference in 10-40 kHz sound levels during solid ice conditions compared to open water or seasonal melting conditions, which may provide a salient acoustic gradient between open water and solid ice conditions by which ice seals could orient so that access to open water for breathing is preserved [15].

Laboratory and field studies have demonstrated that both invertebrates (oyster and crab) and fish use soundscape cues for orientation and localization of appropriate settlement habitat [9,11]. Habitats with greater biodiversity are often associated with richer acoustic soundscapes compared to low diversity habitats, which in itself may be an important cue for animal orientation [2-3,10,17-18]. Stanley et al. [19] measured the sound intensity level required to elicit settlement and metamorphosis in several species of crab larvae, and Simpson et al. [20] discovered that coral reef fish responded more strongly to the higher frequency components (>570 Hz) of the reef soundscape.

An example of the utility of long-term soundscape analysis is the survey of low frequency underwater ocean sound over the past 50 years off the West Coast of the United States. Using a combination of declassified U.S. Navy recordings and scientific data sets, a steady increase in low frequency sound (10-200 Hz) has been documented and mainly attributed to an increase in commercial shipping [21-23]. Sound levels have increased at approximately 3 dB/decade (0.55 dB/yr) up until the 1980s [22-25] and then slowed to 0.2 dB/yr [26]. Most recent measurements in this region show a leveling or slight decrease in the sound levels since the late 1990's despite increases in the number and size of ships [27].

Blue, fin, sei, Brydes, right, and humpback whales all communicate in the 10-200 Hz frequency band; infra-sound from waves crashing onshore (that marine life likely use for orientation) is also in this band. Understanding how marine life uses this frequency band and the effects of human activity is the subject of many soundscape studies. Shipping increases alone do not fully account for the observed 10-12 dB increase in the 20-40 Hz band from 1965 to 2003 [23-24]. Activities from oil and gas exploration and production, as well as from renewable energy sources, have also increased the total sound levels in this band [28]. Biotic sound levels have likely also increased due to recovering whale populations and the 'Lombard effect', which is the increase in call amplitude to compensate for higher noise levels. The Lombard effect has been demonstrated in humans and many animal populations and may contribute to rising low frequency levels as animals vocalize louder to be heard above the noise [29]. Climate change is increasing the amount of glacial ice entering the oceans, and as they disintegrate, they generate low-frequency noise with large source levels that contributes to the regional noise budget for extended periods [30]. The regional limits of soundscapes, even for low frequencies which propagate long distances, is underscored by the differences in long-term sound level increases. While studies have reported a significant increase of ambient noise levels in the North Pacific, current studies in the Indian, South Atlantic, and equatorial Pacific Oceans have not observed a uniform increase in ocean sound levels [7,31]. Very little is known about the global soundscape as a whole, and this is an active area of ocean exploration. Theory and observations suggest that human generated noise could be approaching levels at which negative effects on marine life may be occurring [28].

Exploring the Oceans – Solutions to a Big Data Problem

We are currently experiencing an exponential increase in the volume of passive acoustic data being collected due to more recorders being deployed for longer periods and covering wider frequency ranges. As an example, a joint soundscape project proposed by the authors is expected to generate 40 tera-bytes of passive acoustic data per year for a three-year program. The passive acoustic data will be interpreted and synthesized using regional satellite measurements of ocean primary production, winds speeds and currents, as well as local measurements of acoustic backscatter (zooplankton and fish), temperature, pressure, salinity, and oxygen levels. This is clearly a major data management and analysis problem that will be addressed using proven automated tools and the development of new techniques. An important area of new research are indicators of habitat quality and biodiversity developed for terrestrial applications are now being adapted to marine habitats and soundscapes [4-5,32]. Rapid acoustic analysis of a habitat's soundscape using high level indicators such as the acoustic complexity index (ACI), acoustic entropy index, or acoustic dissimilarity index are providing a quantitative way to assess biodiversity and compare/contrast soundscapes of different areas [3-5, 17] (Figure 6). Bioacoustic indicators are estimated by mathematically assessing the ratio of energy at different spectrum frequencies to make inferences about local community biodiversity. The larger the frequency bandwidth of recordings, the more information is available to accurately capture species and habitat diversity [5].

One of the major challenges in applying indices developed in the terrestrial environment to marine systems is distinguishing whether increased levels of complexity, entropy, or biodiversity were a result of natural biotic signals or increased background noise from human generated or abiotic sources [5,33]. Sound travels further underwater than in air, so noise sources from afar that overlap in frequency with local or regional signals of interest complicate interpretation of the calculated index. One habitat type that has shown particular promise for the application of passive acoustic data to measures of biodiversity is coral reef systems. Healthy coral reefs support high levels of biodiversity and produce an overall soundscape rich in temporal and spectral signatures created by the cacophony of vocalizing animals ranging from low frequency fish calls to high-frequency, broadband sounds from

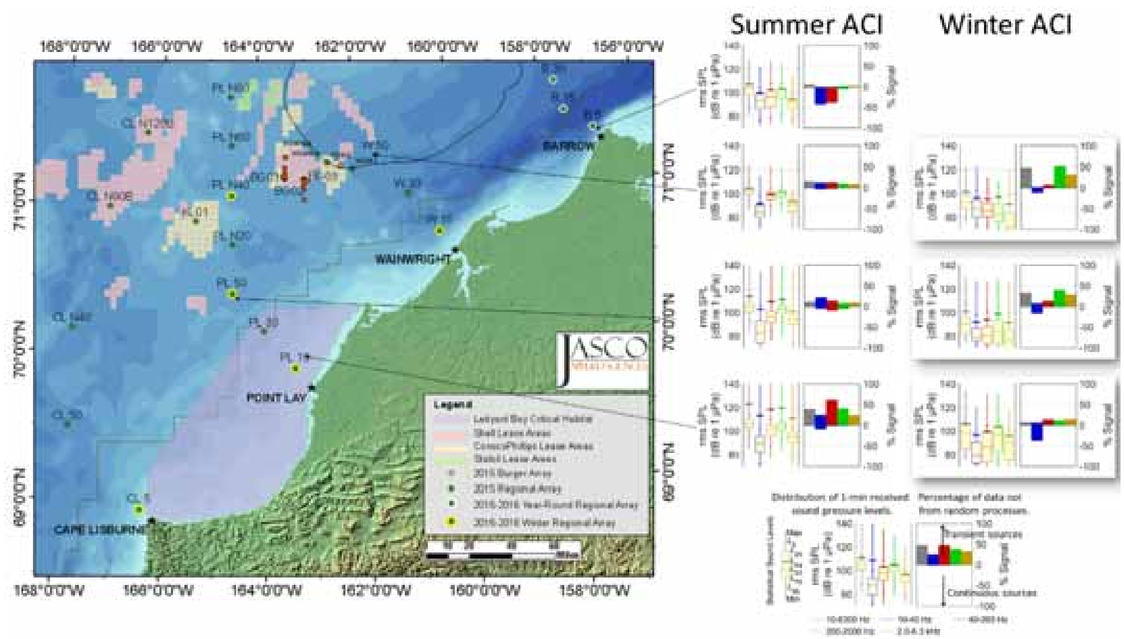


Figure 6. Soundscapes are a big data problem: presentation of average sound pressure levels (box-and-whisker plots) and the acoustic continuity index (bar charts) from 4 of 25 recorders deployed in the Chukchi Sea from 2014-2015. Frequency band colors: gray = 10 – 8000 Hz; blue = 10-40 Hz (waves, vessels); red = 40-200 Hz (vessels, seals, walrus, bowhead whales); Green = 200-2000 Hz (seals, walrus, beluga, bowheads, ice); gold = 2-8 kHz (beluga, ice). The top station (Barrow AK) has significant amounts of shipping in the summer which is a continuous source in the 10-200 Hz frequency bands. 10 NM off Point Lay walrus haulouts create transient sounds in the 10-2000 Hz bands. The winter soundscape has continuous low frequency noise from (10-40 Hz) and the off shore stations have transient energy in the 200-2000 Hz band from bearded seal mating displays.

snapping shrimp. The diversity of coral reef sounds, produced by a wide variety of species, spanning a broad frequency range makes this ecosystem an ideal environment to link species biodiversity with acoustic indicators. Very recent work in the U.S. Virgin Islands has shown that diel trends in low-frequency sound production correlate with reef species assemblages [34], illustrating the potential value of acoustic metrics for monitoring and assessing biodiversity of reef habitats. Further development of soundscape derived indicators will provide useful tools for ecosystem monitoring for a variety of applications such as providing an initial rapid indicator of ecosystem components and complexity of largely unexplored regions.

Summary

There is much to be learned from our terrestrial counterparts as the field of underwater acoustics develops its use and framework for defining, visualizing, and comparing acoustic environments. Ocean sound is not often linear or stationary; thus, examining the spectrum as a whole and as the sum of its different parts provides insight to biology and ocean dynamics that would not be identified otherwise [7,31]. To date, application of the underwater soundscape has only taken into account the measured physical component of the soundscape. Making the perceptual link between the soundscape and marine life cognition is not currently feasible due to our lack of detailed knowledge of marine animal perception. Developing a common vocabulary, measurement parameters, and standard method for displaying soundscape data is critical for a field that strives to understand an environment where sound, as opposed to vision, is the dominant mode of communication and obtaining information, and where the visual link between sound production and source is often limited by distance and the physical barrier of the water surface. Passive acoustics has already provided a wealth of new knowledge about the ocean despite its infancy compared to terrestrial applications. Development of methods to assess marine biodiversity, animal density, and ecosystem status and health will continue to expand passive acoustics a valuable tool for ocean exploration.

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